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Proceedings of the International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames

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PROCEEDINGS OF THE INTERNATIONAL WORKSHOP ON MEASUREMENT AND COMPUTATION OF TURBULENT NONPREMIXED FLAMES

Naples, Italy
July 26-27, 1996

Edited by
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ABSTRACT

This SAND report documents the proceedings of the International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames, held in Naples, Italy on July 26-27, 1996. Contents include materials that were distributed to participants at the beginning of the workshop, as well as a Summary of Workshop Accomplishments that was generated at the close to this Naples meeting.

The Naples workshop involved sixty-one people from eleven countries. The primary objectives were: i) to select a set of well-documented and relatively simple flames that would be appropriate for collaborative comparisons of model predictions; and ii) to specify common submodels to be used in these predictions, such that models for the coupling of turbulence and chemistry might be isolated and better understood.

These proceedings are also "published" on the Web and those interested in the ongoing process of data selection and model comparison should consult the workshop page for the most recent and complete information on these collaborative research efforts. The URL is:

(http://www/ca.sandia.gov/tdf/Workshop.html)

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International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames

Naples, Italy
July 26-27, 1996

Organizing Committee: R. Barlow, R. Bilger, J.-Y. Chen, I. Gökalp, E. Hassel, A. Masri, N. Peters

Contents

International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames

Preface and Objectives

In recent years, there has been important progress in both experimental and computational research on turbulent nonpremixed combustion. We wish to consolidate some aspects of this progress by identifying a set of well-documented and relatively simple flames that can serve as benchmark cases for comparison with model predictions.

The emphasis of this workshop is on fundamental issues of turbulence-chemistry interactions in gaseous, non-sooting flames. The data sets under consideration include simple jet flames, piloted jet flames, and bluff-body stabilized flames. This emphasis is complementary to other collaborative efforts involving more technical flames.

An important objective of the workshop and subsequent collaborations will be to isolate submodels that treat mixing and reaction. To accomplish this it will be necessary to eliminate, minimize, or at least try to understand the differences in model predictions that result from using different chemical mechanisms, different fluid dynamics models, different model constants, different numerical schemes, different thermo-fluid properties, or different radiation models.

This will not be a competition to identify the model that best matches the data, since a model may get the right answers for the wrong reasons. Rather, this is intended as a collaborative exercise to better understand the critical issues in the measurement and modeling of turbulence-chemistry interactions. We want to identify priorities for additional experiments and pathways for potential improvements in a variety of combustion models.

Specific objectives of this workshop are to:

- Select a set of well-documented flames that are appropriate for collaborative comparison of model predictions.
- Determine a process for review and expansion of this collective data base.
- Identify gaps in the existing data base and, if possible, establish priorities and a time table for filling these gaps.
- Establish common submodels, where appropriate, to simplify the task of comparing model predictions.
- Define ground rules for comparison of model predictions.
- Identify an appropriate format for presentation and publication of the results of these collaborative comparisons.

Progress toward these objectives will be documented and distributed at the end of the workshop or during the Symposium week. Workshop results and information on subsequent collaborations will also be published on the Web at:

http://www.ca.sandia.gov/tdf/Workshop.html

International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames

Hotel Majestic, Naples, Italy

Agenda

July 26, 1996

8:00	Registration	
8:30	Introductory remarks	R. Barlow
8:45	Conclusions from the 1st ASCF Workshop	D. Garreton
9:00	Summaries of experimental data sets	R. Barlow *
10:00	Coffee break	
10:15	Issues relating to experimental data sets	E. Hassel *
11:15	Turbulence models and radiation models	J. Janicka *
12:30	Lunch	
1:30	Turbulence-chemistry interactions	R. Bilger *
2:30	Mixing models	C. Dopazo *
3:30	Break	
3:45	Reduced chemistry	S. Pope *
4:45	Open discussion, highlights of recent results	J.-Y. Chen *
(5:30)	Adjourn for day 1	

* Discussion leader

International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames

Hotel Majestic, Naples, Italy

Agenda

July 27, 1996

8:45	Formation of small groups	
9:00	Parallel small-group discussions (Provide written notes to Carla Fugazzi)	
10:30	Coffee break	
10:45	Summaries by group leaders, and discussion of recommendations (Provide written notes to Carla Fugazzi)	A. Masri *
12:30	Lunch	
1:30	Additional discussion as needed	A. Masri *
	Logistics for collaborative comparisons, future events, dissemination/publication of results (Provide written notes to Carla Fugazzi)	R. Barlow *
3:00	Break Distribution of draft recommendations	
3:15	Small group review and revision of draft recommendations	
4:00	Priorities for new research	J.-Y. Chen *
5:00	Closing remarks Distribution of workshop summary	R. Barlow
5:15	Adjourn	

* Discussion leader

General Issues

Standard flames: Should the research community do more to encourage the use of standard flames for validation of both experimental and computational methods?

Number of test cases: How many test cases should be considered?

Blind tests: Should there be blind tests where detailed experimental data are not released until after model predictions have been completed? How much information on the blind test case should be provided before predictions are compared?

Dissemination of workshop results: How should the results of the workshop be publicized? (Options include: mailing summaries to participants, publishing on the Web, printing a report on the proceedings of the workshop, having no organized distribution of results.)

Dissemination of subsequent results: How should results of subsequent data evaluations and model comparisons be presented and published? (Options might include: an edited volume of contributed papers, a special issue of a journal, a special session at an appropriate meeting in 1997 or 1998, a second workshop held in conjunction with an appropriate meeting, no coordinated presentation or publication of results.)

Funding: Do people have flexibility under their current funding to conduct the research associated with this workshop? Are there opportunities for sponsorship of these efforts beyond the support that people have already for ongoing research on turbulent nonpremixed flames?

Screened data sets: Should data sets be screened by a committee, evaluated for accuracy, and checked for inconsistencies before being approved for use in collaborative comparisons of model predictions?

Experimental Issues

Completeness of data base: For what flames are detailed velocity and scalar data sets available? Are the available data appropriate and sufficient for comparison and validation of combustion models? Are there specific additional measurements, that would significantly benefit the process of model validation?

Contradictions among data sets: Are there contradictions among various measurements of similar flames that need to be resolved before model validation can proceed?

Boundary conditions: Are experimental boundary conditions well documented and appropriate for model comparisons? What are the uncertainties in boundary conditions? Are boundary conditions well matched for experiments on the same flame conducted at different locations or at different times?

Measurement uncertainties: How should measurement uncertainties be documented? How should uncertainties in boundary conditions be documented? What accuracy is needed to allow effective evaluation of models. Are the precision and accuracy of the data set under consideration sufficient to allow useful comparisons with model predictions?

Spatial resolution: What are the smallest spatial scales of velocity gradients and scalar gradients in the nonpremixed flames under consideration for this workshop? How should spatial scales be estimated? What direct measurements of spatial scales in flames are available? Are there subsets of the available data that should be avoided because of spatial averaging effects? To what extent can experimental uncertainties due to spatial averaging be quantified?

Data distribution: How should data be distributed? Should it be freely available? What documentation should be included with distributed data? Should the original experimenters retain any control over how these data are processed and presented?

Data format: In what format should the data be made available? Should there be a standard format? What units should be used? Should raw (single realization) data as well as averaged data be available?

Mixture fraction: Should a common definition of the mixture fraction be used? If so, what should it be? Do some definitions yield lower experimental uncertainty than others?

New experimental priorities: In the context of model validation, what are the priorities for new types of experiments and new measurement capabilities?

Modeling Issues

Isolation of submodels: To what extent can the contributions of various submodels be isolated? In particular, how effectively can the submodels for mixing and reaction be isolated to allow an uncluttered comparison of their behaviors?

Chemical mechanisms: Can we identify a reduced mechanism for each fuel system that can serve as a common basis for comparison? What progression of fuels is most sensible for model comparisons?

Turbulence models: Should the prediction of cold jets be considered as part of the comparison process for combustion models? How well do current turbulence models handle reacting jet flows? What tuning is necessary relative to nonreacting flow calculations? Should models be tuned to yield the some level of agreement on the flow field before species concentrations are compared? What tuning is necessary between calculations of different reacting flow geometries or flow condition? Are there regions of jet flames that are not well modeled, such as the thin reaction layers in the first ~20 diameters of a jet flame?

Radiation effects: NO formation is very sensitive to radiation, even in hydrogen flames. Should a common radiation submodel be used in predictions of NO emission? Can we identify a common radiation submodel that may be easily incorporated into the various turbulent combustion models?

Sensitivity to boundary conditions: What assumptions are made regarding boundary conditions that are not measured? (Examples: jet velocity and turbulence profiles at the exit plane, geometric details of the nozzle, boundary layer profile for the coflow, free stream turbulence level and spectrum, coflow temperature and humidity level) How sensitive are predictions to variations in boundary conditions? Do uncertainties in experimental boundary conditions lead to significant uncertainties in predictions?

Sensitivity to model 'constants' and properties: How sensitive are model predictions to changes in model constants or thermo-fluid properties? Should there be a uniform specification of properties to be used in model comparisons? What are the uncertainties in these properties?

Sensitivity to numerics: How sensitive are predictions to details of the numerical schemes?

Bases for comparison: On what bases should model predictions and experimental data be compared? Mean and rms velocity profiles; higher-order velocity statistics; ensemble-, Favre-, and conditional averages and fluctuations of temperature and species; pdfs of various scalars; NO emission index?

Trends versus absolute accuracy: What emphasis should be given to the correct modeling of trends, such as the scaling of NO emissions, as opposed to quantitative agreement on a specific number, such as NO concentration?

Flow complexity: What level of flow complexity is appropriate for comparison of models? What progression of added flow complications (pilot flames, recirculation, swirl, cross flow, complex confinement geometries, lifted flames) is most conducive to model development and validation?

Workshop Questionnaire Results

40 responses were received. Responses to the multiple-choice questions are summarized below.

2. What is the overall nature of your research?

experimental	mostly experimental	equal split	mostly computational	computational
(6)	(8)	(3)	(8)	(14)

basic	mostly basic	equal split	mostly applied	applied
(3)	(18)	(12)	(3)	(0)

3. Considering experimental vs. computational camps, characterize your current or recent direct collaborations with the other camp.

negligible	limited	moderate	frequent	extensive
(1)	(5)	(15)	(12)	(6)

4. If you wanted to participate in some of the collaborative work being encouraged through this workshop, would you have flexibility under your current funding to do so?

yes	not sure	no
(13)	(24)	(1)

5. Do you think the proposed collaborative effort to compare model predictions with experimental measurements could serve as a vehicle for you to obtain additional funding?

yes	not sure	no
(19)	(14)	(4)

6. Should there be a coordinated effort to bring this work to the attention funding agencies?

definitely yes	yes, with reservations	neutral	no, with reservations	definitely no
(12)	(16)	(10)	(0)	(0)

7. Should the combustion community encourage the use of standard flames for validation of experimental and computational methods?

definitely yes	qualified yes	neutral	qualified no	definitely no
(20)	(17)	(2)	(0)	(0)

8. Should blind tests be included in the process of model comparisons?

definitely yes	yes, with reservations	neutral	no, with reservations	definitely no
(12)	(17)	(9)	(1)	(1)

9. Should data sets under consideration for model comparisons be screened and approved by some committee prior to being recommended for use in this process.

yes	not sure	no
(28)	(9)	(2)

10) Indicate topics where you have experience, expertise, or strong interest (check as many as appropriate):

(26) turbulence models
(22) mixing models
(24) reduced chemical mechanisms
(18) detailed chemical mechanisms
(14) reaction zone structure
(21) pdf models
(19) flamelet models
(8) conditional moment closure models
(8) eddy breakup models
(15) modeling of practical systems
(18) comparison of different models
(19) differential diffusion effects
(10) scaling laws for turbulent flames

(15) velocity measurements in turbulent flames
(19) temperature measurements in turbulent flames
(13) Raman scattering measurements
(15) quantitative LIF measurements
(16) line imaging or planar imaging
(13) comparison of measurement techniques
(16) spatial scales in turbulent flames
(12) experimental uncertainty
(13) measurements in practical systems
(17) flame radiation (measured or modeled)
(27) NO formation (measured or modeled)
(7) alternative definitions of the mixture fraction
(2) unsteady effects, soot formation

11) Indicate the fuel and geometry combinations that you would like to see addressed during this workshop. Check as many boxes as you think appropriate.

	H_2	CO/H_2	CH_4	CH_3OH	C_3H_8
Simple jet flames	26	12	29	7	11
Piloted jet flames	13	11	23	5	6
Bluff-body stabilized flames	9	13	23	5	7
Swirl-stabilized flames	9	7	18	5	9

Overview of Some Available Data Sets

The organizers have identified several data sets that appear to be appropriate for the purposes of the workshop. This is a limited list that emphasizes flames where both velocity measurements and detailed multiscalar measurements are available and where the scalar measurements include one or more minor species, such as OH or NO. The list may be expanded or modified based upon the interests of the workshop participants.

H_2 jet flames (including dilution)

TH Darmstadt	Simultaneous measurements of temperature, N_2, O_2, H_2, and H_2O by Raman/Rayleigh scattering in three flames of H_2/N_2 (1:1). LIF measurements of OH and NO. Additional temperature measurements by CARS. Three-component velocity measurements by LDV in the same flames.
DLR-Stuttgart	Simultaneous measurements of temperature, N_2, O_2, H_2, and H_2O by Raman/Rayleigh and NO by laser-induced fluorescence. One condition in common with Darmstadt data, plus several additional flames at varying Reynolds number.
Sandia	Simultaneous measurements of temperature, N_2, O_2, H_2, H_2O, OH, and NO by Raman/Raleigh/LIF in three flames (undiluted, 20% He, 40% He dilution)
ETH Zurich	LDV measurements at the same conditions as the Sandia H_2 and H_2/He flames.

Piloted jet flames

Sydney/Sandia	Simultaneous measurements of temperature and major species in flames of several fuels, including H_2/CO_2, $CO/H_2/N_2$, methane, and methanol. Velocity data for undiluted methane flames only.
Delft	Piloted natural gas flame. LDV, CARS temperatures, OH LIF

Bluff-body-stabilized flames

Sydney/Sandia	Simultaneous measurements of major species concentrations and temperature in flames of methane, methanol, and $CO/H_2/N_2$ with varying degrees on local extinction. Recent data sets also include OH and NO measurements and have been obtained in methanol, CO/H_2, and H_2/CH_4 flames. Velocity measurements in these recent flames are in progress.

Some Additional Possibilities

1. Turbulence data on cold air jets (Wignanski and Fiedler hot wire data, TH Darmstadt three-component LDV data including higher moments, Univ. Dayton three-component LDV data)

2. Recent Sandia scalar data on $CO/H_2/N_2$ jet flames, including NO, that could serve as a blind test case if velocity measurements can be made on the same flames

3. Simultaneous measurements of velocity and density in a hydrogen jet flame (Dibble et al).

4. Data sets on swirl-stabilized hydrogen flames from TH Darmstadt and Univ. Dayton.

3D-LDV-, Raman-, Rayleigh, CARS-, OH- and NO-LIF-, velocity-, temperature- and concentration-data from different turbulent non-premixed H_2/N_2 jet flames

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http://www.th-darmstadt.de/fb/mb/ekt/Welcome.html

Abstract

The aim of the described work is to have a full description of some well defined simple turbulent non-premixed jet-flames, including boundary conditions. A simple jet-flame burner was built, consisting of a fuel tube (diameter 8 or 11 mm) surrounded by an air stream (diameter 140 mm). The flames are vertical burning from bottom to top. Mixtures from H_2 and N_2 (in most cases 50/50 volume percent) are used as fuel. The Reynolds-numbers are 6200 and 10000.

These flames have been measured with:
1) 3D-LDV (velocities)
2) Spontaneous Raman Rayleigh spectroscopy (SRRS) (temperatures and concentrations of major species)
3) CARS spectroscopy (temperatures)
4) LIF (OH and NO concentrations)

Results of LDV, SRRS, and CARS measurements are published and discussed in great detail in [1]. LIF results are published in [2,3].

Boundary Conditions

Table 1 Flame Parameters

Flame name	Nozzle diameter (mm)	Reynolds number	Froude number	Exit velocity (m/s)	Coflow (m/s)
H1	11	10000	6000	25.3	0.2
H3	8	10000	15500	34.8	0.2
H5	8	6200	6000	27.7	0.2

Measurement Techniques

LDV: Three-component velocities and up to the fourth order statistical moments have been measured. Spatial resolution: 0.5 mm x 0.5 mm x 0.5 mm. ZrO_2 particles were used and seeding densities in both streams were kept equal and high enough so that the effective data rate depends on the PC data processing rates. Thus, velocity biasing effects should be negligible.

SRRS: Spontaneous Raman Rayleigh spectroscopy with excimer laser (248 nm) and a diode-line camera using full spectral fit method for data evaluation.
Spatial resolution: 2.5 mm x 0.5 mm x 0.5 mm, temporal resolution: 20 ns.

CARS: Temperature measurements were made using a typical Nd:YAG-Dye laser arrangement, with beams arranged in the USEDCARS configuration. Spatial resolution: 1.5 mm x 0.5 mm x 0.5 mm, temporal resolution: 6 ns.

LIF: OH and NO concentrations and temperature and all major concentrations simultaneously are measured by combining the apparatus of SRRS and CARS. Thus, an excimer laser was used for SRRS, and a Nd:YAG-Dye-wavelength-extender for LIF. By combining Raman and LIF quenching is quantitatively calculated.
Spatial resolution: 2.5 mm x 0.5 mm x 0.5 mm, temporal resolution: 20 ns.

Uncertainty Estimates

For LDV measurements in these flames the overall maximum errors are estimated to be 5% for mean values and 15% for auto- and cross-correlations. Accuracy for the SRRS measurements is estimated to be ±100 K for temperature and ±1 percent for concentrations, based upon measurements in a premixed laminar flat flame. Accuracy of the CARS temperature measurements is estimated as ±50 K. Uncertainties are discussed in references [1-3].
OH and NO concentrations: precision ±20 percent, accuracy ±10 percent.

Summary of Measurements

The diffusion flames were measured on the axis from x/d=0 to 100 with a spacing of $\Delta x/d=5$. The radial profiles were measured at levels x/d=5, 20, 40, 60, 80 with variable spacings from 0.5 mm to 3 mm. For the SRRS and CARS measurements 100 samples were collected at each location and Favre averaging was applied. Velocity data were number averaged.

Many of the results are compared to Reynolds-stress-model predictions and to calculations with reduced chemistry mechanisms.

A burner was also delivered to the DLR Stuttgart, Germany, where some additional measurements are made and compared to the above data.

Availability of Data

The data are available through FTP on a computer in our institute (krause.ekt.maschinenbau.th-darmstadt.de). The data are given in ASCII format. The normalization of the data is shown in the caption of each independent data file. Only averaged data are given.

Existing Model Comparisons

There are some comparisons with model predictions which are discussed in detail in several publications, e.g. [1-3] and ref. therein. One part is compared to Reynolds-stress-tensor calculations with simple fast chemistry, another part (mostly the LIF part) is compared to k-e-model with reduced chemistry.

References

1. T.C. Cheng, G. Fruechtel, A. Neuber, F. Lipp, E.P. Hassel, J. Janicka, "Experimental data base for numerical simulations of turbulent diffusion flames," Forschung im Ingenieurwesen - engineering research, Vol. 61, No 6 (1995)
2. A. Neuber, G. Krieger, M. Tacke, E. Hassel, J. Janicka, "Finite Rate Chemistry and NO Mole fraction in Non-Premixed Turbulent Flames," submitted to Comb. and Flame, June (1996)
3. A. Neuber, K. Krieger, M. Tacke, E. Hassel, J. Janicka, "In-situ measurements of NO in turbulent diffusion flames," Forschung im Ingenieurwesen - engineering research, in press, to appear in Sept. (1996)

Simultaneous Raman/LIF Measurements of Temperature, Major Species, and NO and 2D LIF Imaging in Turbulent H_2/N_2/Air Jet Diffusion Flames

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Abstract

A combined single-pulse spontaneous Raman/LIF system has been used to determine the temperature and the major species and NO concentrations in turbulent H_2/N_2/air jet diffusion flames. Two flames with different N_2 dilutions and Reynolds numbers are characterized by pointwise measurements of radial temperature and concentration profiles at 6 downstream positions. In addition, 4 flames with different jet exit velocities but same fuel compositions are compared. The results show that differential diffusion plays an important role in these flames, especially near the flame base, where the temperature is increased above the adiabatic flame temperature and deviations from adiabatic equilibrium are large. The correlation between NO and temperature in the near field of the jet reveals an unexpected separation into a "lean" and "rich branch" with significantly different NO concentration levels. The visualization of the reaction zone and the fuel jet by 2D LIF imaging shows that two distinct flow regions are present in the near field: a highly turbulent fuel jet and a laminarized flow in the reaction zone. These structures have an important influence on the transport processes in that region of the flame.

Boundary Conditions

The burner for the turbulent diffusion flames consists of a straight stainless steel tube (i.d. 8 mm, length 350 mm) with a thinned rim at the exit and a contoured nozzle (i.d. 140 mm) for supplying coflowing dry air. The presented data sets are from 2 different flames. Flame A: Fuel composition 50% H_2 + 50% N_2 (±0,5%), v_{exit}=21.7 m/s (±0.25 m/s), Re≈6200, coflow 0.32 m/s (±0.02 m/s); Flame B: Fuel composition 75% H_2 (±0.5%) + 25% N_2 (±0.5%), v_{exit}=42.3 m/s (±0.5 m/s), Re≈8800, coflow 0.4 m/s (±0.02 m/s). In addition, the influence of a variation in exit velocity (14.1, 28.2, 42.3, 56.4 m/s) was investigated in flame B.

Techniques

A single-pulse spontaneous Raman scattering apparatus, based on a flashlamp pumped dye laser (2-4 J pulse energy, λ=488 nm), was used for point-wise measurements of the major species concentrations and the temperatures [1,2]. The spatial resolution was 0.6 mm (in x, y, and z direction), the temporal resolution 2-3 µs. The precision is mainly limited by shot noise of the detected photons and was determined in stable flat flames, yielding e.g. for the mole fraction of N_2 at 1950 K: 0.69 ± 0.005 (rel. σ=±0.7%), for O_2: 0.053 ± 0.002 (rel. σ=±3.8%), and for the temperature ±1.5%. The accuracy depends essentially on the quality of the calibration procedure. The main uncertainties of our calibration flames are ±2% for the temperature and ±1% for the gas flows. The error of the gas flow meters resulted in an uncertainty of ≈1% for the concentrations of N_2 and H_2O in the exhaust gas and 3-5% for O_2 and H_2. An additional error could arise from temperature induced drifts of the adjustment between 2 calibration measurements.

The concentrations of nitric oxide were simultaneously measured by laser-induced fluorescence after excitation of the $A^2\Sigma^+$ - $X^2\Pi$ (0-0) transition at λ≈226 nm with a Nd:YAG pumped dye laser [3]. With the knowledge of the temperature and the gas composition, as deduced from the Raman signals, the NO fluorescence signals could be analyzed taking into account Boltzmann fraction, quenching, line shift, and line broadening on a single-pulse basis. The precision, as derived from

NO-doped laminar flat flames, is typically 7-10%, the single-pulse accuracy was estimated as 10-15%.

2D LIF imaging of OH and doped NO (added to the fuel) was used to visualize the structures of the reaction zones and fuel jet (no absolute concentration measurements). In these measurements, the fluorescence distribution from (doped) NO reflects the entrainment of water into the fuel jet in the following sense: In a pure H_2/N_2 mixture, NO fluorescence is very weakly quenched ($Q \approx 3 \times 10^7$ sec^{-1}) resulting in high signal levels, but small admixtures of water enhance the quenching drastically, e.g. 2% water increase the quenching rate by an order of magnitude, leading to a rapid drop in LIF signal intensity. Thus, from the NO LIF distribution regions of pure fuel and the boundary to regions where water from the mixing layer has entrained into the fuel jet can be identified.

Calibration

Calibration measurements for the Raman and NO LIF signals were performed in laminar premixed H_2/air flames stabilized on a flat flame burner (McKenna Products). The characteristics of this burner have been thoroughly studied by CARS, Rayleigh scattering, and flame calculations resulting in a set of 38 "standard flames" covering a range of temperatures from 1230 to 2180 K and of equivalence ratios from 0.3 to 2.0. A further extension of the temperature range down to about 700 K was achieved by using a stainless steel tube as a cooler for the exhaust gas. The operating conditions of the burner as well as the temperatures and gas compositions of most of the "standard flames" can be found in a paper of Prucker et al [3]. For the calibration of the NO LIF signals, the flames were doped with small amounts of NO (up to 100 ppm).

Summary of Measurements

The flames were investigated at the downstream positions x/D = 5, 10, 20, 40, 60, and 80. At each x/D, radial profiles consisting of typically 15 points were measured, each measurement comprising 300 single-pulse values of the temperature, major species, and NO concentrations. In order to get a general characterization of the flames, the mean values and fluctuations of each of these quantities were extracted from the pdf's. For studies of the correlations between these quantities, various scatter plots were built on a single-pulse basis, in some cases conditionally averaged for an easier identification of relations. The comparison of the 4 flames with different exit velocities was performed by measuring a radial profile at x/D = 5 and an axial profile in each flame.

Besides the composition of comprehensive data sets, the main points addressed in the measurements are (1) the influence of differential diffusion on temperature, species distributions, NO production, and mixture fraction f as a conserved(?) scalar; (2) the C_{NO}-T and C_{NO}-f correlations and their dependence on jet exit velocity [4,5].

Single-pulse 2D LIF images of OH and doped NO were recorded in flame B (Re=8800) at downstream positions from 0 to x/D=20. The images support the interpretation of the transport processes, especially in the near field of the jet, where the laminarization of the flow within the reaction zone forms a contrast to the highly turbulent fuel jet [5].

Availability of Data

All single-pulse data of the temperature, major species and NO concentrations, and mixture fractions from the flames are available as (compressed) ASCII files. Mean values and RMS fluctuations, calculated as ensemble (or time) averaged values are also given for each measuring location. The data sets can be submitted on floppy disks.

References

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Simultaneous Measurements of Major Species, OH and NO in Nonpremixed H_2 and H_2/He Jet Flames

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Abstract

Spontaneous Raman scattering, Rayleigh scattering, and laser-induced fluorescence are combined to obtain simultaneous measurements of the major species, temperature, OH, and NO in jet flames of hydrogen and helium-diluted hydrogen. A primary objective of this experimental series is to provide detailed information on thermal NO formation in jet flames. Flow conditions are similar to those reported by Driscoll and Chen [1], who made sampling probe measurements of NO and NO_x. The present data set includes radial profiles at several streamwise locations along the visible flame length for each of three flames: undiluted H_2, 20% He dilution, and 40% He dilution. Dilution reduces radiative loss, and in the most dilute case radiation has only a small influence on thermal NO production. In the context of model validation, dilution allows the effects of the radiation submodel to be isolated from turbulence, chemistry, and mixing submodels. In addition, measurements in the undiluted H_2 flame were made at the visible flame tip for Reynolds numbers from 6000 to 12000, providing some limited information on the Reynolds number scaling of the overall NO emission. Experimental results are discussed in [2,3], and some comparisons with predictions using Monte Carlo pdf and Conditional Moment Closure models have been published in [4,5]. LDV measurements at nominally the same flow conditions are available from ETH Zurich.

Boundary Conditions

The burner was a straight tube with a squared-off end (inner diameter, d=3.75 mm; outer diameter 4.84 mm). This was centered at the exit (30-cm by 30-cm) of a vertical wind tunnel contraction. The coflow air velocity was 1.0 m/s (±0.06 m/s), and the flames were attached and unconfined. Observation of laminar flames (Tsuji and jet geometries) in the facility suggest that coflow turbulence intensity is negligible for the present turbulent flame results. A free-stream turbulence intensity of 2% was measured at a higher mean velocity (40 m/s). The coflow air temperature was 294 K (±2K), and the humidity ratio was between 0.006 and 0.008 kg/kg-air during the course of the experiments. The fuel exit temperature was 295 K (±2K). Fully developed turbulent pipe flow may be assumed at the nozzle exit. Fuel flow conditions are summarized in Table 2. Note that the Reynolds number for the 40% He case was printed in error in [2,3].

Measurement Techniques

Spontaneous Raman scattering was used to measure concentrations of N_2, O_2, H_2, and H_2O. The Rayleigh scattering signal was converted to temperature using a species-weighted scattering cross section, based on the Raman measurements. The beam from a flashlamp-pumped dye laser (532 nm, 5 Hz, ~750 mJ/pulse) was used for the Raman and Rayleigh measurements. Linear laser-induced fluorescence (LIF) was used to measure NO and OH. The two Nd:YAG-pumped dye laser systems were fired approximately 1 and 2 μs before the Raman laser. Quantitative NO and OH concentrations were obtained by correcting these fluorescence signals on a shot-to-shot basis for variations in the Boltzmann fraction and the collisional quenching rate, which were determined from the measured temperature and species concentrations. The NO data were also corrected for the temperature dependent effects of collisional line broadening. Mixture fraction was calculated from the measured species concentrations (moles/l) as:

$$f = \frac{(w_{H2} + \alpha w_{He})([\mathrm{H_2O}] + [\mathrm{H_2}]) + (w_H + \frac{\alpha}{2} w_{He})[\mathrm{OH}]}{w_{N2}[\mathrm{N_2}] + w_{O2}[\mathrm{O_2}] + (w_{H2O} + \alpha w_{He})[\mathrm{H_2O}] + (w_{H2} + \alpha w_{He})[\mathrm{H_2}] + (w_{OH} + \frac{\alpha}{2} w_{He})[\mathrm{OH}]}$$

where the w's are molecular weights, and α is the mole ratio of helium to hydrogen in the fuel stream. Here, the helium-hydrogen ratio is assumed to be unaffected by differential diffusion. Preferential diffusion of He toward fuel-lean mixtures after the hydrogen is oxidized to H_2O may cause some error in the Rayleigh temperatures.

The spatial resolution for all measurements was ~750 μm in each direction. The scalar gradient length scales, λ_B, in these flames were estimated based upon the relation $\lambda_B = 0.38 C_B (x - x_0) Re_d^{-3/4}$, where $(x-x_0)$ is the streamwise distance from a virtual origin and Re_d is the jet Reynolds number. The viscosity of air at an intermediate temperature of 1200K was used in the Reynolds number, and C_B was taken to be 10. For all the streamwise locations reported here the estimated λ_B was greater than the 750 μm measurement resolution by at least a factor of two. However, it is important to note that these estimates are based on correlations for nonreacting jets and that the measurement of scalar gradients in reacting flows is an active area of research.

Calibrations and Uncertainties

The temperature dependent calibration functions for each of the Raman channels were determined by measuring signals from H_2-air flat flames over a wide range of conditions above a Hencken burner. (The Hencken burner is a nearly-adiabatic burner consisting of an array of small fuel tubes arranged in a stainless-steel honeycomb matrix that allows for the flow of air.) OH measurements were referenced to a H_2-air Hencken burner flame at an equivalence ratio of ϕ=0.94 (T~2350 K), where the OH number density was measured by laser absorption. The NO calibration factor was determined by doping lean premixed laminar flames with known concentrations of NO and differencing the signals for two doping levels.

Measurement precision is limited by shot noise in the Raman and LIF signals, shot-to-shot variation in the Raman/Rayleigh laser lineshape, and noise in the laser energy measurement used in determining Rayleigh temperature. Table 1 includes the standard deviations of results in representative calibration flames. Table 1 also includes estimates of potential systematic errors in the measured scalars. These estimates are based on repeatability of Raman calibrations, changes in the Raman/Rayleigh laser characteristics during experiments, drift in the LIF dye laser wavelengths, and uncertainties in the fluorescence calibrations and corrections.

Table 1 Estimates of Experimental Precision and Accuracy

Scalar	% rms	ϕ	T (K)	Conc. (cm^{-3})	Systematic Uncertainty
N_2	3.8	0.94	2350	2.1×10^{18}	±3-4%
H_2O	4.8	"	"	1.0×10^{18}	±3-4%
OH	7.5	"	"	2.2×10^{16}	±15%
T	2.5	"	"	NA	±3%
f	5.1	"	"	NA	±3-4%
NO	12.5	0.5	1550	2×10^{13}	±15-20%

Summary of Measurements

Radial profiles were obtained at several streamwise locations in each of the three flames. Typically, 600-800 samples were collected at each position. In addition, measurements were made on the centerline at x=L (the visible flame tip) in a series of seven flames of undiluted H_2 with Reynolds numbers from 6000 to 12000. Flame lifted-off occurred at higher Re. Flow conditions and measurement locations are given in Table 2.

Table 2 Fuel Flow Conditions and Measurement Locations

H_2:He (by vol.)	u_j (m/s)	Re_d (u_jd/ν)	L/d (visible)	Streamwise Locations (x/L)
100:0	296	10,000	~180	1/8, 1/4, 3/8, 1/2, 5/8, 3/4, 1
80:20	294	9,800	~150	1/8, 1/4, 3/8, 1/2, 5/8, 3/4, 1
60:40	256	8,300	~100	1/2, 3/4, 1

Availability of Data

Single-shot and averaged results are available directly from the corresponding author, and these data will be posted on the internet in the near future. For our own analysis and in response to requests, we have generated single-shot data files of mole fractions, mass fractions, and mole/l concentrations. We have also generated ensemble-, Favre-, and conditional averages of these quantities. Not all formats are currently available for all flames. Our current plan is to post single-shot data for temperature and concentrations (moles/l). Averaged data will be posted in several forms.

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Laser Doppler Velocimetry Measurements in Turbulent Non Premixed Hydrogen/Helium Flames

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1 Abstract

Laser Doppler Velocimetry (LDV) measurements (including the Reynolds Stress tensor) were conducted in a turbulent non premixed hydrogen flame. The hydrogen was diluted with 0%, 20% and 40% helium. The burner was a straight tube (inner diameter 3.75 mm) centered in a coflowing air stream. The flames were similar to the ones investigated by R.S. Barlow and C.D. Carter with Raman/Rayleigh/LIF at Sandia National Laboratories (Barlow and Carter, 1994).
Additionally simple heat flux measurements were performed and for illustration purposes integral video pictures were taken.

2 Boundary Conditions

Geometry The nozzle was a straight, 0.55 m long tube with an inner diameter of 3.75 mm and an outer diameter of 5 mm. It was centered in a vertical wind tunnel with a hexagonal base which had a diameter of 0.6 m. Two of the six tunnel walls were made of glass (Figure 1). To investigate the influence of the slightly different experimental setup of the ETHZ and Sandia, the geometry of the Sandia tunnel (fixed measurement volume, moveable flame and moveable wind tunnel with a square base of 0.3 m side length) was reconstucted for one measurment position. However, for the LDV measurements, no differences between the two setups were found.

Fuel The hydrogen was diluted with 0%, 20% and 40% helium. The mean exit velocities and Reynolds numbers are listed in Table 1. The fuel inlet temperature was 25 $^{\circ}$ $\pm$ 1° celsius.

Dilution %He	Mean velocity at the nozzle [m/s]	Reynolds number
0%	296 $\pm$ 1.5%	10'000
20%	294 $\pm$ 1.5%	10'000
40%	256 $\pm$ 1.5%	8'300

Table 1: Fuel inlet conditions

Coflow The velocity of the coflowing air at a temperature of 25 $^{\circ}$ celsius was 1 m/s. The turbulence intensity was about 10 %, and the mean velocity varied about 1.3 % over the radius.

3 Measurement Technique

Measurement Facility The velocity measurements were performed with a three/two dimensional Laser Doppler Velocimeter from Dantec (one channel got defective during the measurements). The LDV probes were perpendicular and a cross scattering technique was used, which reduced the measurement volume to nearly a spherical shape of 80 μm diameter. The probes were moved with a traverse of 0.05 mm repetition accuracy. Mean data rates varied from 800 Hz to 5 kHz, depending on the seeding density and the laser intensity. Temporarely the data rate raised up to several 10 kHz.
The Doppler frequency was analysed with Burst Spectrum Analyzers (BSA).

Data Analysis With a Shannon algorithm (Veynante and Candel, 1993) the non equal spaced raw data was remapped to a regularly spaced timebase. This procedure reduces LDV biases which occur due to higher measurement probabilities of faster seeding particles and due to conditional sampling. The reliability of the Shannon algorithm was shown by (Veynante and Candel, 1988) and (Flury and Schlatter, 1996). Based on the remapped data, Reynolds averaged mean, rms, and Reynolds Stress tensor components were calculated. Furthermore for the 20% dilution integral time scales were determined.

Radiation Measurements To estimate the radiative heat flux of the flame, a black plate (Figure 2) was moved along the flame at a radial distance of 0.3 m. The temperature of the plate was measured with a calibrated thermocouple. With an additional correction for the convective heat losses the emitted radiation could be determined.

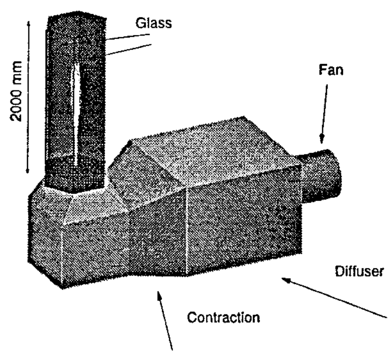

Figure 1: Sketch of the test facility

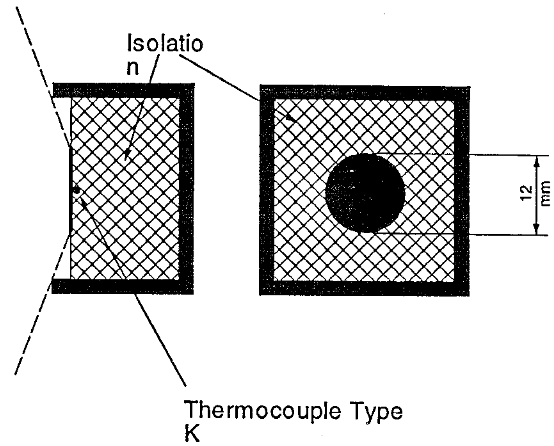

Figure 2: Sketch of the black plate sensor

4 Summary of Measurements

Radial velocity profiles were measured at different axial positions. The distances to the nozzle (Table 2) are related to the visible flame length L according to the definition of Barlow (Barlow and Carter, 1994).

Axial Distance		0% Dilution		20% Dilution		40% Dilution	
		mm	D	mm	D	mm	D
0	L	0	*0*	0	*0*	0	*0*
1/16	L	42	*11*	35	*9*	23	*6*
1/8	L	84	*23*	70	*19*	47	*13*
1/4	L	169	*45*	141	*37*	94	*25*
3/8	L	253	*68*	211	*56*	141	*38*
1/2	L	338	*90*	281	*75*	188	*50*
5/8	L	422	*113*	351	*94*	234	*63*
3/4	L	506	*135*	422	*112*	281	*75*
1	L	675	*180*	562	*150*	375	*100*

Table 2: Downstream position of the radial profiles

5 Availability of Data

The velocity data are available over anonymous ftp from :
`camelot.ethz.ch`
or via :
`http://www.les.iet.ethz.ch/comb/nox/nox.html`.

For each flame and axial distance there is one file with the name: `sxxyy.dat`, where xx is the axial distance in L and yy is the amount of helium. The data files contain a header, describing the measured flame, the axial position and the seeding.

```
# Date          : 18-Mar-96  M.Flury ETHZ CH
# Data File     : s1420.dat
# Raw File      : 1420a
# Re            : 10 000
# Mean out.vel.[m/s]: 294
# Dilution He%  : 20
# Seeding in    : fuel & coflow
# Hight [mm]    : 141
# Hight [L]     : 1/4
# Comment       : Shannon
# Variables     :
# nr x y   z      u      varu v      varv uv
  0      0 12.5  140 22.58 115.23 2.13 56.99 23.52
  2      0 8.5   140 37.2 163.11 2.67 85.04 20.98
```

The variables are:

- nr : index of the measurement point
- x : tangential position in mm
- y : radial position in mm
- z : axial position in mm
- u : axial velocity in m/s
- varu : RMS of the axial velocity in m/s
- v : radial velocity in m/s
- varv : RMS of the radial velocity in m/s
- uv : shear stress component of the Reynold Stress Tensor

The other quantities (Time Scales, Radiation data) are not available on the anonymous ftp server.

6 Existing Model Comparisons

The flames were studied numerically with a Lagrangian type combustion model (Borghi, 1988), which models a skeleton of the joint PDF between mixture fraction and a reactive species. The turbulence is modeled with the k-ϵ model, which was extended to predict the spreading rate of a round jet correctly (Pope, 1978). Details may be found in the publications below.

7 Publications

Schlatter, M. and Ferreira, J.C. and Flury, M.1996. Analysis of Turbulence-Chemistry Interaction with Respect to NO Formation in Turbulent Nonpremixed Hydrogen-Air Flames. *Twenty-Sixth Symposium (International) on Combustion*. The Combustion Institute, Pittsburgh.

Schlatter, M. and Flury, M.1995. Modelling of NO_x Formation in Turbulent H_2 Diffusion Flames. *Third International Conference on Combustion Technologies for a Clean Environment, 3-6th July 1995, Lisbon, Portugal.*

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Flury, M. and Schlatter, M. 1996. Influence of seeding methods on LDV measurements. In *Twenty-Sixth Symposium (International) on Combustion*. The Combustion Institute, Pittsburgh. Work in Progress Poster.

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LDV AND CARS MEASUREMENTS IN SWIRLING AND NON-SWIRLING COAXIAL TURBULENT HYDROGEN JET DIFFUSION FLAMES

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Abstract

This data set includes the velocity and temperature measurements in confined coaxial turbulent hydrogen jet diffusion flames with or without swirl using three-component laser-Doppler velocimetry (LDV) and coherent anti-Stokes Raman spectroscopy (CARS). The combustion system consists of a central fuel tube (9.45-mm i.d., 0.2-mm lip thickness, 806-mm length) and a concentric annulus-air tube (26.92-mm i.d.), centered in a vertical test section (150- × 150-mm rounded-square [near-octagonal] cross section, 486-mm length). The annulus-air swirling angle were varied between 0° and 60° by placing a helical vane swirler unit in the annulus channel 96 mm upstream from the jet exit. This data set provides several unique features, including swirling flame cases rarely available in the literature. The three-component velocity data obtained with a small probe volume (100-μm sphere) are conditioned upon the origin of the fluid flow channel to avoid statistical velocity bias problems. Twenty-one independent moments (including triple correlations) of the probability density functions of the velocity components were determined from a set of 4000 LDV data at each location. Mean and root-mean-square fluctuation temperatures were measured from typically 500 CARS data at each location.

Boundary Conditions

Report No.	Swirler angle θ (°)	Mean velocity		
		Jet U_j (m/s)	Annulus U_a (m/s)	External U_e (m/s)
1	0	25	4	1
2	0	100	20	4
3	30	100	20	4
4	45	100	20	4

The measured velocity and temperature near the exit plane (x = 1.5 mm) can be used as the inlet boundary conditions [1].

Measurement Techniques

Velocity: Three-Component LDV
- Light source: 15 W argon ion laser (Spectra Physics)
- Velocity components: ±45° off jet axis (514.5 nm); tangential (488.0 nm)
- Focusing and collection lenses: $f = 250$ mm
- Frequency shift: 10 MHz (514.5 nm), 20 MHz (488.0 nm)
- Probe volume: approximately 100-μm sphere
- Fringe spacing: 3.6 μm
- Signal processor: counter type (TSI 1990C)
- Coincidence window: 10 μs
- LDV realization: approximately 4000 measured data at each location
- Software filtering: 4-σ method (σ: standard deviation)
- Tracer particle: zirconia (< 1 μm, 97%)

Temperature: CARS
- Light source: Nd:YAG laser (Quanta Ray DCR-2A, 10-ns, 10 Hz, 150 mJ@532 nm)
- Configuration: folded BOXCARS
- Focusing lens: $f = 250$ mm
- Probe volume: approximately 25-μm diameter × 250-μm length
- Spectrometer: 3/4-m grating (Spex 1702)
- Detector: intensified CCD camera (Princeton Instruments)
- CARS realization: approximately 500 measured data at each location

Uncertainty Estimates

Mean velocity: ±2%
2nd order moments: ±5%
3rd and 4th order moments: ±10%
Mean temperature: ±10% near room temperature; ±5% near flame temperature
r. m. s. fluctuation temperature: ±10%

Summary of Measurements

Radial locations: $y = 0$ - 26 mm
Axial locations: $x = 1.5, 10, 25, 50, 75, 150, 225$ mm
Quantities measured:

LDV: 21 independent flow variables
- mean velocities (U, V, W)
- r. m. s. velocity fluctuations ($\sqrt{\overline{u'^2}}$, $\sqrt{\overline{v'^2}}$, $\sqrt{\overline{w'^2}}$)
- second-order moments ($\overline{u'v'}$, $\overline{v'w'}$, $\overline{w'u'}$)
- third-order moments ($\overline{u'^3}$, $\overline{v'^3}$, $\overline{w'^3}$, $\overline{u'^2\,v'}$, $\overline{v'^2\,u'}$, $\overline{v'^2\,w'}$, $\overline{w'^2\,v'}$, $\overline{w'^2\,u'}$, $\overline{u'^2\,w'}$)
- fourth-order moments ($\overline{u'^4}$, $\overline{v'^4}$, $\overline{w'^4}$)

(where u, v, and w represent the axial, radial, and tangential velocity components, respectively; a capital letter indicates the mean value and a lowercase letter with a prime indicates the fluctuation velocity from the mean. The kinetic energy of turbulence, skewnesses, and kurtoses can be derived from these quantities.)

CARS: Mean (T) and r. m. s. temperature fluctuations ($\sqrt{\overline{t'}}$)
(where T indicates the mean value and a t' indicates the fluctuation from the mean.)

Availability of Data

The data set is currently available in an electronic file format (ASCII format). Each computer data file is headed with a FILENAME. The FILENAMEs have the following format for the velocity data: *JdtsVzzz.PPn* (upper case: letter, lower case: number). The definitions of these characters are: *J,* type of jet fluid; *d,* central tube diameter; *t,* central tube lip thickness; *s,* swirler helix angle; *V,* average velocities at the jet exit plane; *zzz,* radial profile's axial position or axial profile; *PP,* LDV particle seeding method; *n,* file ID number, 1 or 2. The FILENAMEs for the temperature data have the same format with the velocity data files with an extension *.T* instead of *.PPn.*

Existing Model Comparisons

The modeling results using the joint velocity-scalar pdf method have been compared with this data set [1].

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LDV MEASUREMENTS IN SWIRLING AND NON-SWIRLING COAXIAL TURBULENT AIR JETS

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Abstract

This data set includes the velocity measurements in confined coaxial turbulent air jets with or without swirl using three-component laser-Doppler velocimetry (LDV). The flow system consists of a central injector tube (9.45-mm i.d., 0.2-mm lip thickness, 806-mm length) and a concentric annulus-air tube (26.92-mm i.d.), centered in a vertical test section (150- × 150-mm rounded-square [near-octagonal] cross section, 486-mm length). The annulus-air swirling angle were varied between 0° and 60° by placing a helical vane swirler unit in the annulus channel 96 mm upstream from the jet exit. This data set provides several unique features, including swirling flow cases rarely available in the literature. The three-component velocity data obtained with a small probe volume (100-μm sphere) are conditioned upon the origin of the fluid flow channel to avoid statistical velocity bias problems. Twenty-one independent moments (including triple correlations) of the probability density functions of the velocity components were determined from a set of 4000 LDV data at each location.

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Report No.	Swirler angle θ (°)	Mean velocity Jet U_j (m/s)	Annulus U_a (m/s)	External U_e (m/s)
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5	45	100	20	4
6	45	25	4	1
7	60	25	4	1

The measured velocity and temperature near the exit plane (x = 1.5 mm) can be used as the inlet boundary conditions [1].

Measurement Techniques

Velocity: Three-Component LDV

Light source: 15 W argon ion laser (Spectra Physics)
Velocity components: ±45° off jet axis (514.5 nm); tangential (488.0 nm)
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LDV: 21 independent flow variables

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r. m. s. velocity fluctuations ($\sqrt{\overline{u'^2}}, \sqrt{\overline{v'^2}}, \sqrt{\overline{w'^2}}$)

second-order moments ($\overline{u'v'}, \overline{v'w'}, \overline{w'u'}$)

third-order moments ($\overline{u'^3}, \overline{v'^3}, \overline{w'^3}, \overline{u'^2 v'}, \overline{v'^2 u'}, \overline{v'^2 w'}, \overline{w'^2 v'}, \overline{w'^2 u'}, \overline{u'^2 w'}$)

fourth-order moments ($\overline{u'^4}, \overline{v'^4}, \overline{w'^4}$)

(where u, v, and w represent the axial, radial, and tangential velocity components, respectively; a capital letter indicates the mean value and a lowercase letter with a prime indicates the fluctuation velocity from the mean. The kinetic energy of turbulence, skewnesses, and kurtoses can be derived from these quantities.)

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Simultaneous Measurements of Major Species, OH and NO in Nonpremixed $CO/H_2/N_2$ Jet Flames

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Abstract

Spontaneous Raman scattering, Rayleigh scattering, and laser-induced fluorescence are combined to obtain simultaneous measurements of the major species, temperature, OH, and NO in jet flames of $CO/H_2/N_2$ (40:30:30 by volume). The data set includes radial profiles at several streamwise locations along the visible flame length for two flames with different nozzle diameters but the same Reynolds number of 16,700. These are recent measurements that benefit from several improvements to the Raman/Rayleigh/LIF systems implemented over the past two years. These data have not yet been published or distributed, and thus they <u>may be useful as a blind test for models</u>. There is a need for velocity measurements to complement the scalar data.

Boundary Conditions

The burners were straight tubes with squared-off ends. The smaller tube had inner and outer diameters of 4.58 mm and 6.34 mm, while the larger tube had inner and outer diameters of 7.72 mm and 9.46 mm. The flames were centered at the exit (30-cm by 30-cm) of a vertical wind tunnel contraction. The coflow air velocity was 0.65 m/s (±0.04 m/s), and the flames were attached and unconfined. The coflow air temperature was recorded for each data file. Turbulence intensity in the coflow was ~2%. Fully developed turbulent pipe flow may be assumed at the burner exit.

Measurement Techniques

Spontaneous Raman scattering was used to measure concentrations of N_2, O_2, H_2, H_2O, CO, and CO_2. The Rayleigh scattering signal was converted to temperature using a species-weighted scattering cross section, based on the Raman measurements. Two Nd:YAG lasers (532 nm, 10 Hz) were used for the Raman/Rayleigh measurements, instead of the flashlamp-pumped dye laser described previously. Laser energies were measured using two pyro-electric joule meters, and several modifications to the collection optics and data acquisition system were implemented. These changes have improved the precision and accuracy of the measurements relative to those quoted for the H_2/He flame experiments, particularly for the temperature measurements which now has a precision (rms) of ~1% at flame conditions. Linear laser-induced fluorescence (LIF) was used to measure NO and OH, as described in the summary on H_2/He flames. The spatial resolution for all measurements was ~750 μm in each direction. Use of the Nd:YAG lasers for the Raman measurements allows for more extensive calibrations than were possible with the flashlamp-pumped dye laser system, and systematic errors due to changes in laser lineshape are eliminated.

Summary of Measurements

Radial profiles were obtained at streamwise locations of 20, 30, 40, 50, and 60 nozzle diameters in each of the two flames of $CO/H_2/N_2$. Each radial profile includes 10 to 20 positions, depending on the steepness of gradients. Centerline profiles were also obtained with measurements at 5d intervals from x=20d to x=75d. Typically, 800-1000 samples were collected at each spatial location.

Availability of Data

These data have not been published or distributed. They could be used for a blind test of model predictions if there is sufficient interest.

VELOCITY, OH-CONCENTRATION AND TEMPERATURE MEASUREMENTS IN A PILOTED NATURAL GAS DIFFUSION FLAME.

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ABSTRACT

LDA, CARS, LIF and PLIF measurements have been performed in natural gas flames. The burner consists of a round fuel tube (diameter 6 mm) and an annulus (inner diameter 15 mm., outer diameter 45 mm) for primary air supply. The composition of the Dutch natural gas is (in mole fractions) 81.3 % methane, 2.8 % ethane, 14.3 % nitrogen, 0.9 % carbon dioxide and 0.7 % other hydrocarbons. The pilot flames are positioned at the rim between central pipe and annulus. The flame environment is confined in a octagonal glass chamber (57 mm. wide) with a low velocity uniform air flow to prevent large scale reciculations. Variations of the natural gas velocity, the primary air velocity and the primary air temperature (295 K and 675 K) resulted in six flames. Visualisations of the OH-concentration fields in these flames clearly show the different turbulent structures with extinction phenomena most prominent in the flames with the highest gas and primary air velocities disappearing in the preheated flames. One of the flames has been examined most thoroughly and will be presented in the data set.

BOUNDARY CONDITIONS

Mean velocities:
U_{fuel} = 21.9 m/s
U_{ann} = 4.4 m/s
U_{cofl} = 0.3 m/s

All inlet streams at room temperature, 295 K

- uniform profiles for fuel inlet
- profiles from developed annulus flow for annulus, calculated using standard k-epsilon model with wall functions
- uniform profiles for outer coflow

This leads to a set of profiles that are available in the data set.

MEASUREMENT TECHNIQUES

LDA:

A 2D back scatter LDA system was used. Size of the measuring volume: 0.15 x 2.1 mm.

Statistical uncertainties 1 to 1.5 % in averaged velocities, 2.5 % in rms values. The differences between ensemble averaging and residence time weighted averaging was only present (up to 3 %) in the peak maxima of the rms distributions.

CARS:

A folded BOXCARS arrangement was used resulting in an interaction length of the Stokes and pump beams of 0.9 mm. Temporal resolution: 6 ns. The uncertainty of the mean temperatures varies with the position in the flame. In regions with steep gradients the CARS temperatures are too low by as much as 160 K. In regions without steep gradients the uncertainty is about 50 K. Averaged temperatures compared well with thermocouple measurements. Calibrations in a flat flame from a McKenna burner resulted in temperatures within 25 K with numerical simulations.

LIF:

1D measurements with measuring volume depth of approximately 0.75 mm. Temporal resolution of 6 ns. Calibration has been done in a rich and a lean laminar flame from the McKenna burner. Estimated uncertainty of the averaged OH concentration is 50 %

SUMMARY OF MEASUREMENTS

We have radial profiles at axial positions 50, 100, 150, 200 and 250 mm.

- mean axial velocity
- mean radial velocity
- rms-values of the axial velocity
- rms-value of the radial velocity
- the turbulent kinetic energy
- The Reynolds stress $\overline{u'v'}$
- Mean OH concentrations
- rms OH-concentrations
- Mean temperatures
- rms values of temperature

The LDA measurements have also been performed very close to the burner exit at axial position of 3 mm. Also pdf's of velocities, OH-concentrations and temperature are available.

The data will be made available on an anonymous ftp-site before the end of June.

In our own Heat Transfer Section we have modelled this flame with assumed shape pdf models as well as Monte Carlo pdf models combined with different chemical models.

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Turbulent Nonpremixed Flames Stabilised on a Piloted Jet Burner

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Abstract

The piloted jet burner was developed at the University of Sydney, Australia, and is proven to be a useful tool to investigate streaming (parabolic) turbulent nonpremixed flames for variety of fuels and wide range of Reynolds Numbers. The geometry of the burner is relatively simple and consists of an axisymmetric jet with a thin wall nozzle and an annulus where the pilot gases burn. The hot gases from the pilot stabilise the main flame to the nozzle which forces extinction to occur at higher jet velocities. The pilot flame gases have the same C/H and O/H ratios as that of the main fuel so that the combustion products of both the pilot and the main fuel are indistinguishable. The flames are axisymmetric and the boundary conditions are relatively simple and well defined.
Flowfield data as well as temperature and composition data are available. The flowfield data are collected at the University of Sydney using a conventional LDV technique and consist of radial profiles of mean and rms fluctuations of the axial and radial velocity components for a range of axial locations. The flowfield data are available for selected flames only. Temperature and composition data are instantaneous points measurements collected at the Combustion Research Facility, Sandia National Laboratories, Livermore CA. Measurements have been made using the Raman/Rayleigh/LIF technique to give instantaneous and simultaneous temperature and concentration of various species at a single point in the flame. The species measured are: N2, O2, CH4 (or CH3OH), CO, CO2, H2, H2O, OH. A range of fuel mixtures and flame velocities from low to close to extinction are

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available. The objective of this work is to provide a comprehensive bank of data which may be used by modelers of turbulent nonpremixed combustion.

Boundary Conditions

Table 1 contains a list of fuels and flow conditions measured for this burner. In all of these flames the burner have a fuel jet nozzle which extends to more than 40 jet diameters upstream of the burner exit plane to ensure fully developed pipe flow of the jet. The burnt pilot gas velocity is calculated from the unburnt pilot gas velocity assuming ideal gas behaviour and using the adiabatic pilot flame temperature. The pilot gases are at stoichiometric conditions. The wind tunnel has a 2% turbulence intensity in the free stream. All flames are visibly symmetric and clean of soot. Measured boundary conditions and more detailed information for the piloted jet burner may be found in [1].

Measurements Uncertainty

There are many factors which may contribute to the overall error associated with the measurements presented here. These include shot noise, electronic noise, error associated with the optical set-up and spatial resolution error. Other sources of errors which are specific to the Raman set-up include the cross talk between the Raman signals, the fluorescence interference from soot precursors and other molecules and the interpolation for the Raman calibration factors.
Masri et al.[1] have a detailed analysis of the error estimates concerning this set of data. Figure 1 shows the signal to noise ratios for selected scalars over a range of number densities and temperatures. More details on the calculations of the signal to noise ratios can be found in the data set for the bluff-body burner in this publication. For the plotted scalars the range of signal to noise ratios were: 20 to 60 for the Rayleigh signal, 8 to 40 for O_2 signal, 5 to 20 for the H_2O and H_2 signals, ~ 14 for the CO_2 signal and up to 40 for the CH_4 signal. The signal to noise ratios presented here include shot noise, electronic noise and error associated with the optical set-up but do not account for interferences and spatial resolution error. The fluorescence interference from soot precursors (mainly in the rich side of the flame) varies in intensity depending on the fuel and on the Raman signal. Flames with high hydrocarbon fuels are most affected and among the Raman channels the CO line suffers the highest interference levels.

Two colour LDV system with frequency shifted beams are used to measure the horizontal and vertical velocity components. The fuel and the air are seeded in order to reduce the seeding bias. The uncertainties of the LDV technique is mainly associated with the seeding bias due to steep temperature gradient and the presence of more than one particle in the probe volume. The error due to seeding bias is very hard to quantify and is believed to be small however the error due to the presence of more than one particle in the measurement volume is believed to be $\sim 4\%$ for the mean and $\sim 7\%$ for the rms fluctuations.

Spatial Resolution

Spatial resolution issues for this data set are discussed by Masri et al. [1]. They reported a variance

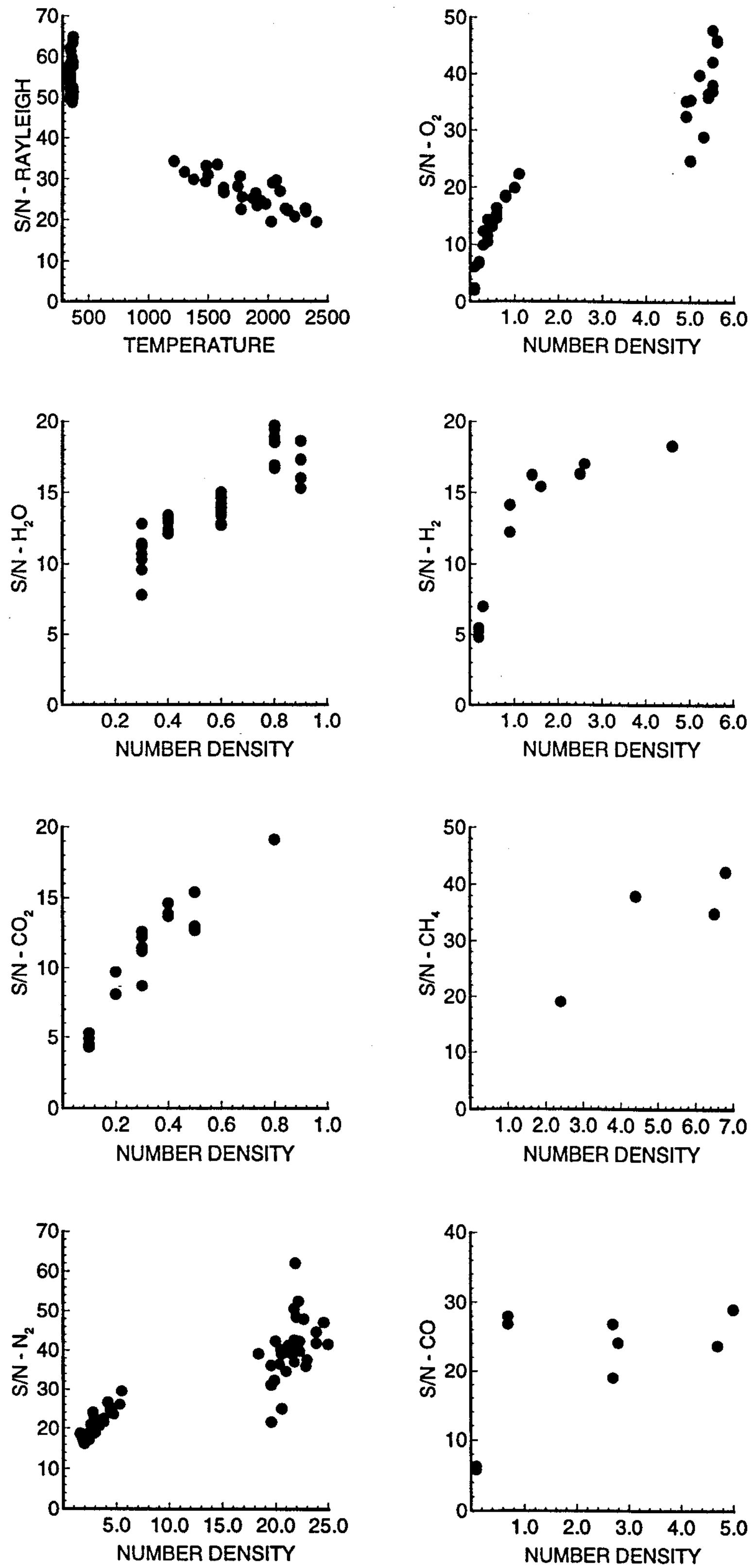

Figure 1: Signal to noise ratio (S/N) for the Rayleigh signal plotted versus temperature and for Raman signals plotted versus number density (10^6 * molecules/cm^3).

Flame	Fuel Mixture	D_J	D_P	U_J	U_P	U_{CO}	T_{IN}	ξ_s
1	CH_4	3.8	10	41–67	3.0	10	298	0.055
2	CH_4	7.2	18	36–55	3.0	15	298	0.055
3	CH_3OH	7.2	18	66–128	3.0	15	373	0.135
4	CH_3OH/AIR(1:1)	7.2	18	105–152	2.1	15	373	0.256
5	CH_3OH/AIR(1:2)	7.2	18	141–169	2.1	15	373	0.377
6	CH_3OH/N_2(1:1)	7.2	18	87–116	3.0	15	373	0.226
7	CH_3OH/N_2(1:3)	7.2	18	68–85	3.0	15	373	0.360
8	H_2/CO_2(1:1)	7.2	18	130–260	2.0	15	298	0.370
9	$H_2/CO/N_2$(1:3:2.67)	7.2	18	98–164	1.0	15	298	0.370
10	$CH_4/H_2/CO/N_2$(1:3:4.5:11)	7.2	18	61–90	1.0	15	298	0.370
11	$CH_4/H_2/N_2$(1:16:7.4)	7.2	18	33–49	1.0	15	298	0.370

Table 1: Piloted flames for which composition and/or flowfield measurements have been made. In this table, D_J is the jet inner diameter (mm), D_P is the annulus inner diameter (mm), U_J is the jet bulk velocity (m/s), U_P is the pilot unburnt bulk velocity (m/s), U_{CO} is the coflow air velocity (m/s), T_{IN} is the temperature of the fuel at the jet exit plane (K) and ξ_s is the stoichiometric mixture fraction

in the measured scalars of 3% to %16 and that most of the PDF is resolved by the measurements.

Data Available

For most of the flames listed in Table 1 a comprehensive sets of data are available covering many axial and radial location in the flame. At least 500 shots are available for each measurement location. Scalars measured for these flames are : Temperature, Mixture Fraction, N_2, O_2, CH_4(or CH_3OH), CO, CO_2, H_2, H_2O, OH. The flow field measurements are available for flame 2 only. For more information regarding this and other data please contact Dr Assaad Masri at the University of Sydney or check our Web page at (http://www.me.su.oz.au/research/energy/energy.html).

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Turbulent Nonpremixed Flames Stabilised on a Bluff-Body Burner

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Abstract

The bluff-body burner is a useful tool to study turbulent nonpremixed flames with recirculating (elliptic) flows. The burner geometry is simple, its boundary conditions are well defined and it has a stable flame for a wide range of coflow and jet conditions. The burner consists of a straight tube centered on a larger cylinder which is mounted on a wind tunnel. The gap between the two tubes is sealed with ceramics to minimize the heat loss to the burner. Burners with a range of bluff-body diameters and fuel jet diameters have been investigated. Spontaneous, single-point measurements of NO, OH, temperature and the major species using the Raman/Rayleigh/LIF technique are available. Also available, are means and rms fluctuations of the radial and axial velocity components measured using conventional two color LDV technique for some of the flames. Flames studied have fuel mixtures ranging from simple H_2/CO to complex CH_4, H_2/CH_4, CO/CH_4 and gaseous methanol. Data are available for different fuel jet velocity flames and at different axial and radial locations along the full length of most flames. The temperature and composition data are collected at the Combustion Research Facility, Sandia National Laboratories, Livermore, California. The flowfield data are collected at the University of Sydney, Australia.

Boundary Conditions

Table 2 contains a list of fuels and flow conditions measured for this burner. For all the cases listed in this table the burner have a fuel jet nozzle which extends to more than 40 jet diameters upstream of the burner surface to ensure fully developed pipe flow at the exit of the jet. The wind tunnel has a 2% turbulence intensity in the free stream. All flames looked visibly symmetric and clean of soot. The burner surface is well insulated and heat transfer to the burner is negligible. Measured boundary conditions and more detailed information on the bluff-body burner may be found in [1].

Measurements Uncertainty

There are many factors which may contribute to the overall error associated with the measurements presented here. These include shot noise, electronic noise, error associated with the optical set-up and spatial resolution error. Other sources of errors which are specific to the Raman set-up include

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the cross talk between the Raman signals, the fluorescence interference from soot precursors and other molecules and the interpolation for the Raman calibration factors.
In order to reduce the error associated with the Raman and Rayleigh measurements made at Sandia's Combustion Research Facility, a number of modifications have been recently introduced. The most important of these modifications is the use of two Nd:Yag lasers for the Raman/Rayleigh measurements instead of the pumped-dye laser (DIANA) which suffers from lineshape changing due to the dye aging. Another modification to the experimental rig is mounting the Rayleigh detector outside the polychromator to reduce the interference of the strong Rayleigh signal on the weak Raman signals. To improve the calibration of the Raman species, a heater is used to cover a wider range of temperatures especially in the lower end of the scale. The calibration gases are heated up to 800°C and Raman/Rayleigh measurements are taken at 100°C intervals providing calibration data between ambient and flame temperatures. The flow-meters used in this experiment were also calibrated using a bank of Laminar Flow Elements.

These modifications have led to an improvement of the signal to noise ratio over previous measurements. This is clearly illustrated in Figure 1 which shows the signal to noise ratio obtained from the calibration data of the Rayleigh signal, a range of Raman signals and the OH LIF signal. A comparison of the signal to noise ratios for these measurements show a clear improvement over the whole range of each scalar has been made. The signal to noise ratios for the Rayleigh signal range from ~ 150 at temperatures of $\sim 2500K$ to ~ 400 at room temperature. However, the ratios for the Raman species and OH increase with number density and range from ~ 10 to ~ 60 depending on the species. For N_2, which is not shown here, the signal to noise ratio ranges from ~ 65 to ~ 125. Note that the ratios presented here include shot noise, electronic noise and error associated with the optical set-up and do not account for interferences and spatial resolution error. Table 1 shows estimates of the percentage error on various species for two typical samples collected in a methane/hydrogen flame using the new and old experimental setup. It is important to note that the measurements in the last two flames listed in Table 2 were obtained using the old experimental setup. The error estimates reported in Table 1 under 'Error Old' apply for these flames.

Lean and rich sample compositions are obtained from the actual data and are taken here as illustrations of typical measurement conditions. The percentage error increases with decreasing number density or mole fraction as shown in Fig. 1. At a mole fraction of $\sim 5\%$ the error is about 5% on CO_2 and 8% on CO increasing to 9% when the mole fraction is $\sim 2\%$. Water at a mole fraction of $\sim 12\%$ has an associated error of $\sim 4\%$. In general, and for mole fractions of $\sim 1\%$ or higher the percentage error on the Raman species is $\sim 10\%$ or lower.

It should be emphasised that the errors reported here do not include the effect of interferences and spatial resolution. Raman interferences affect only selected species and are believed to have a small contribution to the overall error. The fluorescence interference from soot precursors (mainly in the rich side of the flame) is very low in these flames and that improves the signal to noise ratio in all the affected Raman signals. Flames with high hydrocarbon fuels are most affected and among the Raman signals the CO line suffers the highest interference levels. The uncertainty on the NO measurements was reported by Barlow and Carter [2], and the maximum estimated error was reported to be $\sim 20\%$.

For the LDV measurements the green and blue beams from the Argon-Ion laser are shifted by 10 MHz to resolve the velocity direction. The jet and the coflow are seeded and 400 data points are collected for each location with minimum fixed intervals. The error associated with the seeding bias due to steep temperature gradients is hard to quantify and is believed to be small. However, the estimated error from other sources including the velocity bias is believed to be $\sim 4\%$ for the mean and $\sim 7\%$ for the rms fluctuations.

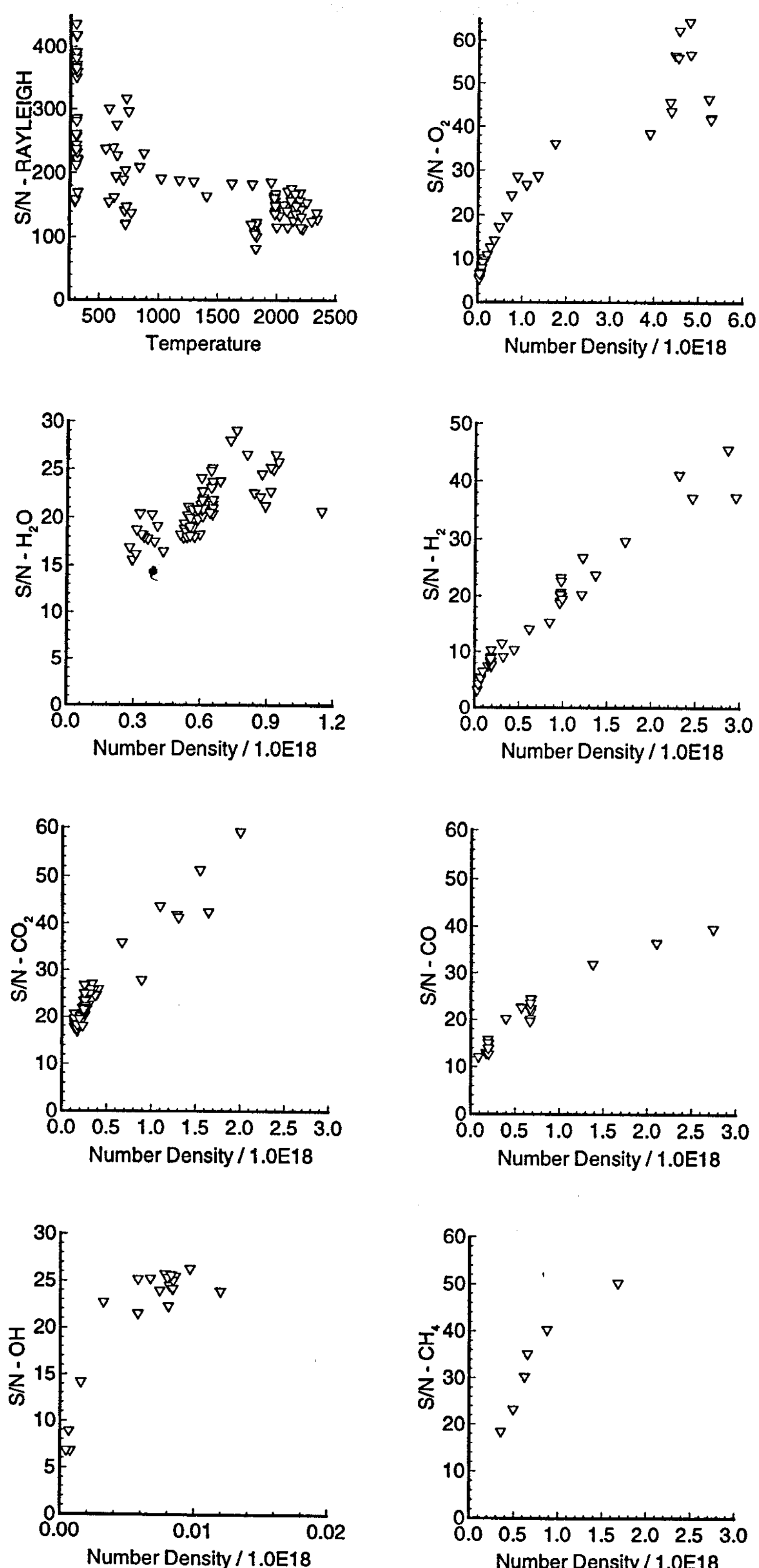

Figure 1: Signal to noise ratio (S/N) for the Rayleigh signal plotted versus temperature and for Raman signals plotted versus number density (10^6 * molecules/cm^3)

Sample	Temperature	Species	% Mass Fraction	Number Density	% Error New	% Error Old
Lean	1900	CH4	0.0	0.0	—	—
		O_2	4.0	0.12E18	10.0	17.0
		N_2	75.0	2.63E18	0.8	5.00
		CO_2	8.0	0.18E18	4.5	11.10
		CO	2.0	0.07E18	9.0	16.60
		H_2	0.5	0.23E18	12.5	0.18
		H_2O	11.0	0.60E18	5.0	7.10
		OH	0.3	0.02E18	3.8	—
Rich	1400	CH4	18.0	1.09E18	2.3	10.00
		O_2	0.0	0.0	—	—
		N_2	57.0	1.98E18	1.1	6.25
		CO_2	5.5	0.12E18	5.5	12.00
		CO	5.5	0.19E18	8.3	10.00
		H_2	2.5	1.22E18	4.0	6.90
		H_2O	12.0	0.65E18	4.0	7.14
		OH	0.0	0.0	—	—

Table 1: Sample estimates of the error associated with selected species for two typical sample compositions taken from measurements in flame of H_2/CH_4 fuel. % Error New is for the new setup, % Error Old is for the old setup.

Spatial Resolution

The spatial resolution effects on the various scalars measured in turbulent flames using the Raman/Rayleigh/LIF technique have been studied by Mansour et al.[3], who give an estimate of those effects on the measured variance of the scalar quantities in terms of the l_p/L_θ, Re_t and l_p/L_u. Here l_p is the length of the measurement probe volume; L_u, is the integral length scale; and L_θ, the scalar microscale. The turbulence Reynolds number is defined as: $Re_t = u'L_u/\nu$ where u' is the rms fluctuation of the velocity and ν is the laminar kinematic viscosity. For the experiment reported here, $l_p = 1mm$, $L_u = 10mm$ in the inner region (taken as the width of the inner vortex) and $15mm$ in the outer region (taken as the width of the outer vortex close to the burner), $L_\theta = 80$ at location (x/D_B=0.26 and $r/R_B = 0.06$) where Re_t is maximum at 12200 and 9 at the core of the outer vortex ($r/R_B \geq 0.25$) where $Re_t = 830$. The rms fluctuations of the velocity u' has not been measured and is taken from the calculated velocity field of the same flames and conditions using the Reynolds Stress model for turbulence and the "Mixed is Burnt" combustion model.
Using a chart introduced by Mansour et al.[3] the estimated error due to spatial resolution is determined as the ratio of the variance of the scalar θ that would be measured given the probe dimensions and the flow field details; and the actual variance of the same scalar θ, ($< \theta'^2_m > / < \theta'^2 >$). In these bluff-body flames the maximum spatial resolution error estimated from the chart is 9% at x/D_B=0.26 and r/R_B=0.06 and at all measurement locations where $r/R_B \geq 0.25$ the error is less than 4%. These are acceptable levels knowing that the probe volume is about five times larger than the Kolmogrov length scale.

Data Available

For most of the flames listed in Table 2 comprehensive sets of data are available covering the full

Flame	Fuel Mixture	D_J/D_B	U_J/U_{CO}	Re_J	% B.O.	T_{IN}(K)	ξ_s
1	CH_3OH	3.6/50	80/40	23700	55	373	0.135
2	CH_3OH	3.6/50	121/40	35900	84	373	0.135
3	H_2/CO (2:1)	3.6/50	134/40	17500	22	298	0.135
4	H_2/CO (2:1)	3.6/50	321/40	41990	53	298	0.135
5	H_2/CH_4(1:1)	3.6/50	118/40	15800	50	298	0.05
6	H_2/CH_4(1:1)	3.6/50	178/40	23900	75	298	0.05
7	H_2/CH_4(1:1)	3.6/50	214/40	28700	91	298	0.05
8	CH_4/H_2(2:1)	2.0/50	154/25	15200	90	298	0.052
9	CH_4/CO(1:1)	2.0/50	99/25	12200	95	298	0.114

Table 2: Bluff-body flames for which composition and/or flowfield measurements have been made. In this table, D_J is the jet diameter (mm), D_B is the bluff-body diameter (mm), U_J is the jet velocity (m/s), U_{CO} is the coflow air velocity (m/s), Re_J is the jet Reynolds number, % B.O. is the percentage ratio of jet velocity over the blow off velocity, T_{IN} is the temperature of the fuel at the jet exit plane and ξ_s is the stoichiometric mixture fraction

length of the flame. Scalars measured for these flames are : Temperature, Mixture Fraction, N_2, O_2, CH_4(or CH_3OH), CO, CO_2, H_2, H_2O, OH and NO. Data for flames 8 and 9 do not have OH and NO measurements reported for them. The flowfield measurements are available for flame 7 only. Velocity measurements for other flames may become available in the near future. For more information regarding this and other data please contact Dr Assaad Masri at the University of Sydney or check the combustion Web page at (http://www.me.su.oz.au/research/energy/energy.html).

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International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames

Naples, Italy
July 26-27, 1996

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International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames

Summary of Workshop Accomplishments

July 27, 1996

Sixty-one people from eleven countries participated in this workshop, which was marked by active discussions and a strong consensus that the collaborative efforts proposed by this workshop will be valuable. The primary objectives of the workshop were achieved, namely the selection of a few well-documented flames to serve as a first round of standard cases, the specification of common submodels to be used (where appropriate) in model calculations of these standard flames, and the definition of some ground rules for comparison of model results.

On the second day of the workshop, four discussion groups were formed to provide recommendations on specific issues.

Group	Leaders
Experimental Data Sets	Hassel, Masri
Turbulence Models and Radiation	Janicka, Gore
Mixing Models and Reduced Chemistry	Pope, Dopazo
"Standard" Flames of the Future	Bilger

The recommendations of these groups are outlined on the following pages, which include the names of those people who have kindly agreed to serve on committees or complete certain tasks.

It was agreed that opportunities for new funding to support this international collaborative research effort should be explored. A committee comprised of Bilger, Barlow, Gökalp, Janicka, Just, Pope, and Rahn will pursue strategies for approaching funding agencies.

It was also agreed that more workshops on this topic should be held. Initial plans are to have a work-in-progress workshop in one year, possibly at Sandia/California. The committee listed above will investigate opportunities to obtain travel funding, and they will also look into the possibility of holding the work-in-progress workshop in conjunction with and appropriate turbulence or combustion meeting during the summer of 1997. A pre-27th-Symposium Workshop on Measurement and Modeling of Turbulent Nonpremixed Flames will be planned for Boulder, Colorado in 1998.

Information generated through this workshop and the ongoing collaborations will be made available through the Web site that has already been established for the workshop. This will include:

- descriptions of the selected data sets and links to sites where the data are available
- links to other data sets for nonpremixed flames that are available but have not been selected for this first round of comparisons
- information on recommended submodels, and "reference" calculations for some of the standard flames.

The committee for the Web site will be: Hassel, Meier, Barlow, Pope, Masri, Gore, Lindstedt

It is anticipated that the results of these collaborative comparisons, together with descriptions of the data sets, will be published in an edited volume and should make a significant contribution to the archival combustion literature.

Summary of the Experimental Data Set Group

It was decided that for this first round of collaborative comparisons we will focus on a relatively small number of flame data sets that have both detailed scalar measurements (temperature and species) and LDV measurements. The available data sets were discussed by the full workshop and then screened by this subgroup.

1. Completeness of data sets:

- an axial profile and radial profiles at several locations, giving results at 50-300 spatial points
- u, v, u', v'
- species mass fractions and temperature (Reynolds and Favre averaged)
- mixture fraction f according to the general Bilger formula
- single-shot data in absolute (non-normalized) units

2. Boundary conditions:

- u, v, u', v' profiles at the exit, or 2-3 velocity profiles within the first few diameters
- jet bulk velocity and temperature, coflow velocity and temperature, ambient humidity, burner geometry, fuel composition

3. Measurement uncertainties

- An error estimation for every measured or evaluated quantity is strongly encouraged.
- Error estimation for u, v and rms values
- Scalar data: estimates of precision based upon rms of results in calibration flows and additional estimation of potential systematic error from known sources, such as repeatability or calibration uncertainty

4. Spatial resolution is to be given

5. Selected data cases

Burner	Fuel	b.c.	flow field	mixing field	Scalars	NO	Group
Nonreacting jet	C_3H_8	X	X	X			Dibble/Schefer
Reacting jet	$H_2/N_2 = 1/1$ H_2/He (3 cases)	X X	X X	X X	Raman, T, OH Raman, T, OH	X X	Darmstadt/DLR Sandia/Zurich
Piloted flame	CH_4	X	X	X	Raman, T	-	Sydney/Sandia
Nonreacting bluff body	To be done						
Reacting bluff body	$CH_4/H_2 = 1/1$	X	X	X	Raman, T, OH	X	Sydney/Sandia

- Every effort should be made to get these data sets onto the Web within the next 3 months.

7. Additional comments:

- the differences from the mixture fraction definition should be investigated
- a list of references for the experimental set-ups and ~ procedures should be available
- an estimate of the smallest flame length scales would be very welcome for each test case
- a disclaimer for each FTP side would be appropriate

Summary of the Turbulence Model Group

The group agreed over the following issues:

1. For a selected number of "standard" flames, "reference" predictions shall be provided.

   - Jets
     "Cold" jet calculations and one flame calculation should be carried out by Gore and Janicka.

   - Bluff Body
     Bluff body calculations will be carried out by Peeters.

   - Swirling Flows
     If standard swirling flow has been established (presumably within the next year) reference calculations will be carried out by Takagi and Janicka. These calculations shall be based on a simple "standard" combustion model (f, g - approach with equilibrium model and presumed β-pdf). All details of the completed model, all boundary conditions as well as grid dependence will be carefully documented.

2. The calculations will be carried out with recommended turbulence models. These are:

   - Jets. Standard k-ε-model with $C_\varepsilon = 1.60$, Jones-Musonge Reynolds-stress model.

   - Bluff Body. Same as jets.

   - Swirling Flows. Standard k-ε-Model with swirl corrections and Jones-Musonge Reynolds-stress model.

3. The group recommends strongly that:

   - all changes of constants should be carefully documented
   - boundary conditions should be given for scalar and velocity fields
   - grid dependence should be shown

4. To provide the necessary information to the community a subcommittee (Gore, Peeters, Sanders, Takagi, Janicka) shall review the prediction for the selected objects.

Mixing Models

Three relatively simple models are recommended as "standards." Each one has known defects.

1. LMSE (Dopazo, 1975)

$$\frac{d\underline{\phi}}{dt} = -\frac{1}{2} C_\phi \frac{\varepsilon}{k} \left(\underline{\phi} - \langle \underline{\phi} \rangle \right), \qquad C_\phi = 2.0$$

2. Modified Curl Model (Janicka & Kollman, 1976). Uniform distribution, $C_\phi = 2.0$

3. Binomial Lagrangian Model. To be made available on the Web by Prof. Dopazo.

Recommendations for reporting data.

1. Conditional means ± conditional r.m.s. shown on scatter plots.

2. Marginal PDF's of ξ, T, CO, OH and O.

Reduced Chemistry

It would be desirable to have consistent full, skeletal and reduced mechanisms for H_2, CO, CO_2 and CH_4 including chemistry that have been tested for a wide range of appropriate conditions. As these do not exist at present, the following recommendations are a compromise. They are recommended as a "standard" to provide consistency between different model calculations. They do not necessarily represent the best available mechanisms.

1. H_2 Lindstedt, Selim & Lockwood (1995), Lindstedt & Selim (1995). Full mechanism and 4, 5 and 7-step reduced mechanisms (including NO). NO chemistry can be removed to produce 2-step reduced mechanisms.

2. $H_2/CO/CO_2$. The same as for H_2 with the addition of CO+OH $\Leftrightarrow$ CO_2 + H with the rate given by Rightley and Williams (1995).

3. CH_4. Full mechanisms
   GRI 1.2 - without NO
   GRI 2.11 - with NO

Skeletal and reduced mechanisms. Hewson and Bollig (1996, 26th Comb.Symp.)

The CHEMKIN mechanism files for each mechanism should be made available on the Web.

Report on Radiation

Thermal radiation from flames reduces the local temperatures sufficiently to affect the production rates of pollutants such as NO. In order to include this effect into turbulence-chemistry models for simple jet diffusion flames, a highly simplified treatment of radiative heat loss is needed.

The flames selected for baseline model evaluation and development involve H_2, H_2/N_2 and H_2/He mixtures injected in the fuel stream. This simplifies the radiation calculations, since only H_2O bands are involved. Radiative heat loss is a nonlinear function of water concentration and temperature; hence, the fluctuations lead to turbulence-radiation interactions. Therefore, average temperatures and average concentrations cannot be used. Mean radiative heat loss (optically thin) can be calculated using integration of a source term convoluted with a joint probability density function of appropriate scalars such as mixture fraction and enthalpy. It is important to note that this PDF should be time averaged thus increasing the temperature dependence.

The Planck mean emission coefficient should be used to calculate optically thin (emission only) radiative heat loss. The RADCAL program by Grosshandler of NIST is most convenient for generating the Planck mean absorption coefficient data.

A list of references on coupled radiation and turbulence calculations is being assembled. Contributions to this list from workshop participants and others are welcome.

The action items are:

1) Measurements of radiative heat fluxes for the Sandia/Darmstadt H_2/air and H_2 + He/air flames, and $CO/H_2/N_2$ flames. Gore and Barlow have made preliminary arrangements to make these measurements within the next 3-6 months.

2) Reference coupled calculations on the Web for the Darmstadt "H_3" flames.

Group Report on "Standard" Flames of the Future

Introduction

Our views became focussed after agreeing on the following premises:

- Improvements in modeling the effects of turbulence on chemistry will remain a leading edge issue for some time (at least 3 years).
- The spontaneous Raman probe will remain a unique measurement tool that enables mixture fractions to be determined in conjunction with reactive scalars.
- Recommendations should not over-reach the likely capabilities of experimenters and/or modellers.

Jet Flames

Unpiloted and piloted jet diffusion flames should continue to be a major thrust of experiments within the following as examples of what should be worthwhile.

- completion of databases on intermediate fuels such as H_2/CO and H_2/CO_2 with good measurements of CO, NO and radiation loss.
- use of the now identified "standard" H_2/N_2 flames as a base from which more complex kinetics can be studied by addition of small amounts of NH_3, methylamine (source for HCN), CH_4, etc. The aim is to test modeling capability for secondary reactions occurring at equivalence ratios of 2 to 3 and hence quite separate from the main reaction zone.
- use of the now identified standard H_2/N_2 flames as a basis for investigation by advanced techniques such as 2D/3D imaging and as a calibration for other diagnostics.

Jets into Hot Coflow

Development of new experimental configurations involving a simple jet in a coflow of hot combustion products in geometries accessible to spontaneous Raman measurements should be pursued. They will provide better simulations of the reaction/mixing situations inherent in:

- recirculation zones where fuel mixes with products rather than air (Dibble)
- NO_x reburn where methane is injected into (cooled) near-stoichiometric combustion products

Confined Axisymmetric Flows

There is a need to prove turbulent chemistry modeling in "elliptic" flows. Confined flows will be more realistic simulations of industrial combustors than bluff-body flows in a surrounding unconfined airstream. Accessibility for spontaneous Raman measurements is essential. Swirling flows to be included. Data will also be important for improving flow and mixing models.

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